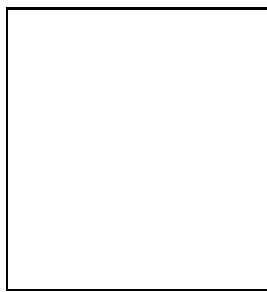


# THE AIR-FLUORESCENCE YIELD

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Detection of the air-fluorescence radiation induced by the charged particles of extensive air showers is a well-established technique for the study of ultra-high energy cosmic rays. Fluorescence telescopes provide a nearly calorimetric measure of the primary energy. Presently the main source of systematic uncertainties comes from our limited accuracy in the fluorescence yield, that is, the number of fluorescence photons emitted per unit of energy deposited in the atmosphere by the shower particles. In this paper the current status of our knowledge on the fluorescence yield both experimental and theoretical will be discussed.

## 1 Introduction

Fluorescence telescopes have been successfully used for the detection of ultra-high energy cosmic rays ( $> 10^{18}$  eV) since the pioneering Fly's Eye experiment<sup>1</sup>. In this technique the fluorescence radiation induced by the charged particles of the extensive air shower generated by a primary cosmic ray is registered at ground by wide-angle telescopes. Assuming that the intensity of the air-fluorescence light is proportional to the energy deposited in the atmosphere by the shower, this technique provides a nearly calorimetric measure of the energy of the primary cosmic ray. Therefore it has the advantage, as compared with methods relying on simulations (e.g. surface arrays working in standalone mode), of being nearly model independent. In spite of this advantage, fluorescence telescopes are presently limited by the uncertainty in the fluorescence yield, that is, the calibration parameter which converts number of fluorescence photons into absolute energy units. For instance in the Pierre Auger Observatory<sup>2</sup> the uncertainty in the fluorescence yield contributes a 14% to the total systematic error in the energy calibration which is presently 22%.

In order to improve the accuracy of this parameter, dedicated laboratory experiments<sup>3</sup> are carrying out precise measurements of the air-fluorescence emission. In these experiments an

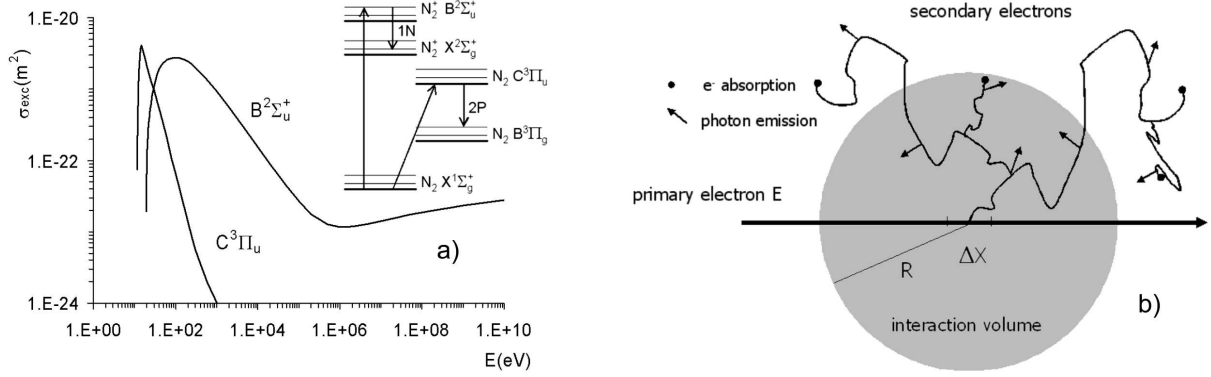


Figure 1: a) Molecular levels of  $N_2$  and  $N_2^+$  involved in the generation of air-fluorescence and cross section versus electron energy for the excitation of the corresponding upper levels. b) At high electron energy most of the fluorescence light is generated by secondary electrons.

electron beam excites air at certain pressure and temperature conditions. A large set of experimental parameters are measured, not only the absolute value of the fluorescence yield but also the spectral features of the fluorescence radiation and the dependence with atmospheric parameters (pressure, temperature, humidity, etc.). On the other hand, progress on the theoretical understanding of the various processes leading to the air-fluorescence emission is being carried out <sup>4</sup>.

## 2 The generation of air fluorescence excited by electrons

### 2.1 Physical processes

Air-fluorescence in the near UV range (300 - 400 nm) is basically produced by the de-excitation of atmospheric nitrogen molecules excited by the shower electrons. Most of the fluorescence light comes from the 2P System of  $N_2$  and the 1N System of  $N_2^+$  (Fig. 1a). Excited molecules can also decay by collisions with other molecules (collisional quenching). This effect which grows with pressure  $P$ , reduces the fluorescence intensity by a factor  $1 + P/P'_\lambda$ . The characteristic pressure  $P'_\lambda$  is defined, for a given  $v - v'$  band of wavelength  $\lambda$ , as the one for which collisional quenching and radiative decay have the same probability.

Basically two different parameters are being used for the energy calibration of fluorescence telescopes. The first one  $\varepsilon_\lambda$  is the number of photons of a given molecular band emitted per electron and unit path length,  $\varepsilon_\lambda = N \times \sigma_\lambda / (1 + P/P'_\lambda)$ , where  $N$  is the density of nitrogen molecules and  $\sigma_\lambda$  is the cross section for the excitation of the molecular band. The second parameter is the *fluorescence yield*  $Y_\lambda$ , defined as the number of photons emitted per unit deposited energy.

$$Y_\lambda = Y_\lambda^0 \frac{1}{1 + P/P'_\lambda}, \quad Y_\lambda^0 = \frac{A_\lambda}{(dE/dX)_{dep}}. \quad (1)$$

$Y_\lambda^0$  is the fluorescence yield in the absence of quenching.  $A_\lambda$  and  $(dE/dX)_{dep}$  are respectively the number of emitted photons at zero pressure and the deposited energy both per unit mass thickness. The fluorescence yield as defined in (1) is more useful for calorimetric applications. Notice that for the determination of  $Y_\lambda$ , both photon number and deposited energy has to be measured in the same volume. This is particularly important for laboratory experiments carried out in small gas chambers. In this case secondary electrons ejected in ionization processes might escape the field of view of the optical system before depositing all the energy (Fig. 1b). In next section the role of secondary electrons in the generation of air-fluorescence light is described.

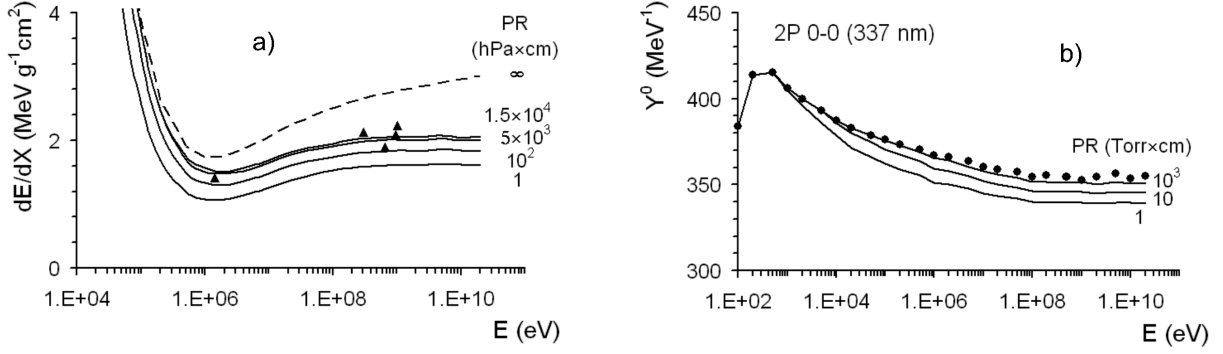


Figure 2: a) Continuous lines represent the energy deposited per unit mass thickness versus electron energy for several values of  $PR$ . Dashed line is the total energy loss of the electron. Triangles represent the relative values of the air-fluorescence yield measured by Kakimoto *et al.* b) Fluorescence yield at zero pressure versus primary energy for the 337 nm band.

## 2.2 Secondary electrons

Secondary electrons from ionization processes are the main source of fluorescence light, since the excitation cross sections show a fast decrease with energy (Fig. 1a), in particular the one for the 2P system. A high energy electron loses energy as a result of collisions with air molecules. Ionization processes give rise to the ejection of secondary electrons which deposit their energy within a certain distance from the interaction point (Fig. 1b). The average energy deposited per unit mass thickness inside a given volume around the interaction point can be expressed as

$$\rho \frac{dE_{dep}}{dX} = N_{air} \{ \langle E_{dep}^0 \rangle + \langle E_{dep} \rangle \} \sigma_{ion}(E), \quad \langle E_{dep}^0 \rangle = \langle E_{exc} \rangle \frac{\sigma_{exc}}{\sigma_{ion}} + I + \langle E_{exc}^{ion} \rangle, \quad (2)$$

where  $\rho$  is the air density,  $N_{air}$  is the number of air molecules per unit volume and  $\sigma_{ion}$  is the ionization cross section. The average energy deposited in the medium by the primary electron per primary ionization process  $\langle E_{dep}^0 \rangle$  is obtained from several molecular parameters<sup>a</sup>. The energy deposited in the volume by the secondary electrons  $\langle E_{dep} \rangle$  is calculated by a dedicated simulation<sup>4</sup>. Figure 2a) shows the result for a sphere of radius  $R$  (Fig. 1b). As expected, the deposited energy depends on  $PR$  and for an unlimited medium,  $PR \rightarrow \infty$ , equals the energy loss predicted by the Bethe-Bloch theory.

Neglecting the collisional quenching, the number of photons emitted per electron and per unit path length can be expressed by  $\varepsilon_\lambda(P) = \rho A_\lambda = N \{ \sigma_\lambda(E) + \alpha_\lambda(E, P) \sigma_{ion}(E) \}$ , where  $\alpha_\lambda(E, P)$  is the average number of photons generated inside the volume per secondary electron, also calculated in the simulation. A very simple expression for  $Y_\lambda^0$  can be obtained from the above equations

$$Y_\lambda^0 = \frac{N}{N_{air}} \times \frac{\frac{\sigma_\lambda}{\sigma_{ion}} + \alpha_\lambda}{\langle E_{dep}^0 \rangle + \langle E_{dep} \rangle}, \quad (3)$$

This procedure allows theoretical predictions on the absolute value of  $Y_\lambda^0$  and its dependence on the electron energy as shown below.

## 2.3 Fluorescence emission versus deposited energy

The energy calibration of fluorescence telescopes relies on the assumption that the intensity of fluorescence light is proportional to the energy deposited in the atmosphere, that is, the

<sup>a</sup>ionization potential  $I$ , total excitation cross section  $\sigma_{exc}$ , average excitation energy of neutral molecules  $\langle E_{exc} \rangle$  and of ionized molecules  $\langle E_{exc}^{ion} \rangle$ .

fluorescence yield is assumed to be independent on the electrons energy. The validity of this assumption can be theoretically checked by means of the model described above. Fig. 2b) shows  $Y^0$  versus  $E$  for the most intense band of the 2P system (0-0 transition at 337 nm). The results shown in this plot can be summarized as follows. The fluorescence yield decreases with  $E$  about a 10% in the range 1 keV - 1 MeV and about 4% in the interval 1 MeV - 20 GeV. This smooth dependence of the fluorescence yield on  $E$  has no impact on the energy calibration of fluorescence telescopes. The proportionality assumption has been also verified experimentally by several groups<sup>5</sup>.

### 3 The dependence of the fluorescence yield on atmospheric parameters

Fluorescence yield depends on pressure, temperature  $T$  and humidity. Thus for a precise energy calibration of fluorescence telescopes these dependencies have to be determined accurately.

As mentioned above collisional quenching reduces the fluorescence emission by a factor  $1 + P/P'_\lambda$ . In the general case, for a mixture of gases (e.g. nitrogen, oxygen, water vapor, etc.), the characteristic pressure obeys the law

$$\frac{1}{P'} = \sum_i \frac{f_i}{P'_i}, \quad P'_i = \frac{kT}{\tau} \frac{1}{\sigma_{Ni} \bar{v}_{Ni}}, \quad \bar{v}_{Ni} = \sqrt{\frac{8kT}{\pi \mu_{Ni}}}, \quad (4)$$

where  $f_i$  is the fraction of molecules of type  $i$  in the mixture,  $\sigma_{Ni}$  is the collisional cross section which depends on the particular band, and  $v_{Ni}$  and  $\mu_{Ni}$  are the relative velocity and reduced mass of the two body system N-i respectively.

The experimental procedure for the determination of the dependence of fluorescence yield on the above parameters is the following. At a fixed temperature the dependence of fluorescence intensity on pressure is measured for dry air. This measure, if properly carried out<sup>b</sup>, allows a determination of  $P'$  and therefore the dependence of the fluorescence yield on pressure at a fixed temperature. Experimental values of  $P'$  for the molecular bands of the 2P and 1N systems in dry air at room temperature have been reported by many authors<sup>3</sup>. The most complete set of  $P'$  values have been reported very recently by AIRFLY<sup>6</sup> improving the accuracy of previous measurements. This set of values are being used by the Pierre Auger Observatory<sup>2</sup> for the calculation of the dependence of the fluorescence yield versus altitude<sup>c</sup>.

The  $P'$  parameter depends on temperature because the collision frequency grows with  $\sqrt{T}$  as predicted by the kinetic theory of gases. In addition the collisional cross section depends on the kinetic energy of the encounters following a power law ( $\sim T^\alpha$ ). Assuming this effect is negligible, the temperature dependence of the fluorescence yield can be easily predicted by equation (4). Recently some experimental works<sup>5</sup> have found a noticeable variation of the collisional cross section with temperature. According to the preliminary values reported by AIRFLY<sup>7</sup>, neglecting this effect results in an overestimation of the fluorescence yield by an amount going up to  $\approx 20\%$  for the 1N (0-0) 391 nm band.

Water molecules have a significant cross section for the air-fluorescence quenching and therefore humidity modifies the value of  $P'$ . Several authors<sup>5</sup> have measured the dependence of fluorescence intensity on humidity. A decrease of the fluorescence yield up to a 20% is found (at 100% relative humidity). From these measurements, values of the characteristic pressure for the quenching with water molecules  $P'_{H_2O}$  have been determined for the main molecular bands of nitrogen.

<sup>b</sup>the effect of secondary electrons escaping the field of view might introduce systematic errors.

<sup>c</sup>the contribution of the pressure dependence to the total uncertainty in the energy determination has been reduced to a 1%.

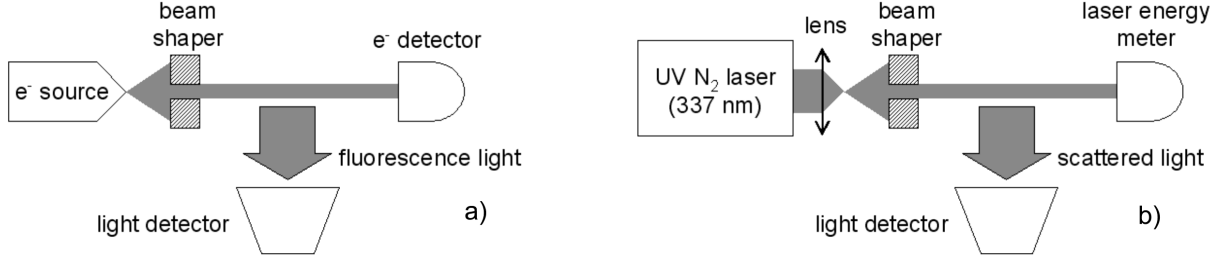


Figure 3: Comparison of fluorescence signal generated by a) an electron beam with b) that from Rayleigh scattering of a nitrogen laser. This procedure allows the absolute calibration of the optical system.

#### 4 Absolute value

The accurate measurement of the absolute value of the fluorescence yield is an experimental challenge. The value is obtained as the ratio  $Y_\lambda = N_\lambda / (N_e \times EDEP)$ . For the measurement of the absolute number of fluorescence photons in the wavelength interval of interest  $N_\lambda$ , the efficiency of the various elements of the collection and detection system has to be known accurately. The number of electrons traversing the observation region  $N_e$  has to be absolutely measured as well. Finally the total energy  $EDEP$  deposited in the volume from where the registered fluorescence was emitted has to be determined (usually by means of a Monte Carlo simulation). In order to reduce systematic errors in the optical calibration (e.g. PMT quantum efficiency, transmission of optical elements, geometrical factors, etc.) some techniques have been developed, based on the comparison with well known physical processes like Cherenkov emission or Rayleigh scattering (Fig. 3).

Several measurements of  $Y_\lambda$  are presently available<sup>3</sup>. Unfortunately the comparison is not simple since some authors report the experimental result of  $\varepsilon_\lambda$  (i.e. photons/m) while others provide  $Y_\lambda$  (i.e. photons/MeV). In addition the spectral intervals of the various experiments use to be different. A detailed summary of the available results can be found elsewhere<sup>5</sup>. Here we will compare some representative experimental data (Tab. 1). For this comparison, measured values of  $\varepsilon_\lambda$  are converted into fluorescence yields using our results on deposited energy. Notice that deposited energy is weakly dependent on the size of the region and therefore a rough estimate of the equivalent  $R$  value is sufficient. From these results the fluorescence yield  $Y_{337}$  for the most intense band, 2P (0-0) at 337 nm, is calculated using the experimental relative intensities reported by AIRFLY<sup>6</sup>. Finally the  $Y_{337}$  values have been normalized to 293 K temperature and 1013 hPa pressure using equations (1) and (4). This procedure is appropriate for a comparison of measurements with typical uncertainties of about 13% or higher. Results are shown in last column of Tab. 1.

Firstly, the  $\varepsilon_\lambda$  values of Kakimoto *et al.* in the range 300-400 nm at several energies have been superimposed in Fig. 2a) to the energy deposited at atmospheric pressure assuming an observation volume with  $R$  ranging between 5 and 15 cm. The comparison of fluorescence intensity (photons/m) with deposited energy has allowed the determination of the fluorescence yield (photons/MeV) in that wavelength interval.

The  $\varepsilon_{337}$  value of 1.021 photons/m from Nagano *et al.* has been combined with the deposited energy for  $R \approx 5$  cm giving the corresponding  $Y_{337}$  value. For the determination of the fluorescence yield, both MACFLY and FLASH calculate the deposited energy from a MC simulation. For these experiments only the conversion for wavelength intervals as well as minor  $T$  and  $P$  corrections were necessary. Finally AIRFLY reports a preliminary value of  $Y_{337}$  determined from the ratio of the absolute number of photons and the energy deposited according to a GEANT4 simulation.

Table 1: Comparison of data on fluorescence yields. Experimental results are used to infer the value of the fluorescence yield for the 337 nm band at  $T = 293$  K and  $P = 1013$  hPa (last column). See text for details.

Experiment	$\Delta\lambda$ nm	T [K]	P [hPa]	experimental result	$I_{337}/I_{\Delta\lambda}$	$Y_{337}$ [MeV] <sup>-1</sup>
Kakimoto <i>et al.</i>	300 - 400	288	1013	see text	0.278	5.4
Nagano <i>et al.</i>	337	293	1013	1.021 ph./m	1	5.5
MACFLY	290 - 440	296	1013	17.6 ph./MeV	0.261	4.6
FLASH 07	300 - 420	304	1013	20.8 ph./MeV	0.276	5.6
AIRFLY (prelim.)	337	291	993	4.12 ph./MeV	1	4.0

## 5 Conclusions

Our understanding on the processes leading to generation of air fluorescence has increased significantly in the last years<sup>5</sup>. The world-wide campaign for the experimental determination of the fluorescence yield has achieved remarkable results, in particular in the measurement of the various dependencies with atmospheric parameters. The fundamental assumption of proportionality between fluorescence intensity and deposited energy has been verified both theoretically and experimentally.

In regard with the determination of the absolute value of the fluorescence yield new data are available. However the interpretation of the results is not straightforward. A comparison using the procedure discussed here shows a general agreement with typical differences of about 15%. For a real improvement in the accuracy of fluorescence telescopes an uncertainty better than 10% in the fluorescence yield is necessary. Several experiments claim high accuracy, for instance, the reported uncertainty of the FLASH experiment is of about 8%. In addition the AIRFLY collaboration will publish soon a final absolute value with an error below 10%. A discussion on these and other high accuracy measurements have been presented elsewhere<sup>5</sup>. Discrepancies between these experiments go beyond the reported accuracies and therefore some experimental effort is still necessary to clarify the situation.

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